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# Landsat Thematic Mapper: Detection of Shifts in Community Composition of Coral Reefs

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**Abstract:** We assembled a time series of 20 Landsat thematic mapper images from 1982 to 1996 for Key Largo, Florida, to ascertain whether satellite imagery can detect temporal changes in coral reef communities. Selected reef and control areas were examined for changes in brightness, spectral reflectance, band ratios, spatial texture, and temporal texture (pixel-to-pixel change over time). We compared the data to known changes in the reef ecosystem of Carysfort Reef and terrestrial sample sites. Changes in image brightness and spectral-band ratios were suggestive of shifts from coral- to algal-dominated community structure, but the trends were not statistically significant. The spatial heterogeneity of the reef community decreased in the early 1980s at scales consistent with known ecological changes to the coral community on Carysfort Reef. An analysis of pixel-scale variation through time, termed temporal texture, revealed that the shallow reef areas are the most variable in regions of the reef that have experienced significant ecological decline. Thus, the process of reef degradation, which alters both the spatial patterning and variability of pixel brightness, can be identified in unclassified thematic mapper images.

Mapeador Temático Landsat: Detección de Desplazamientos en la Composición de Comunidades en Arrecifes de Coral

**Resumen:** Ensamblamos una serie de tiempo de 20 imágenes del mapeador temático Landsat de 1982 a 1996 para Cayo Largo, Florida para determinar si las imágenes de satélite pueden detectar cambios temporales en las comunidades de arrecifes de coral. Los arrecifes de coral y las áreas control fueron examinados para cambios en resplandor, reflectancia espacial, proporciones de las bandas, textura espacial y textura temporal (cambios pixel a pixel a través del tiempo). Comparamos los datos de cambios conocidos en el ecosistema de arrecife de Carysfort y en muestras de sitios terrestres. Cambios en el resplandor de la imagen y en las proporciones de las bandas espectrales sugirieron desplazamientos en la estructura comunitaria dominante de coral a algas; sin embargo, las tendencias no fueron estadísticamente significativas. La heterogeneidad espacial de la comunidad de arrecifes disminuyó en los inicios de los años 1980s en escalas consistentes con cambios ecológicos conocidos en la comunidad de coral del arrecife Carysfort. El análisis de la variación a nivel de pixel a través del tiempo, e identificado como textura temporal, reveló que las áreas de arrecifes bajos son las más variables en regiones donde el arrecife ha experimentado disminuciones ecológicas significativas. Por lo tanto, el proceso de degradación, que altera tanto los patrones espaciales como la variabilidad del resplandor de pixeles, puede ser identificado en el Mapeador Temático sin clasificar.

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## Introduction

Remote sensing offers the potential to observe the responses of coral reef ecosystems to perturbations on a geographical scale not previously accessible. But coral reef en-

vironments are optically, spatially, and temporally complex environments that present difficult challenges for extracting meaningful information about the ecology and vitality of coral reef communities. One of the keys to using remote sensing to assess coral reef "health" is the development of a methodology, reef bio-optics, that relates the remotely sensed satellite signal to the optical signal generated by coral reef environments. Using a bio-optical approach, it may be feasible to remotely map benthic habitats.

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Paper submitted April 5, 2000; revised manuscript accepted February 7, 2001.

Traditional marine science has always utilized in situ monitoring to detect community change, but the archival record of satellite-based information contains synoptic mesoscale information that could also be tapped to examine long-term environmental change in the coral reef ecosystems. This approach becomes more attractive when one considers the remoteness of most reefs and the expense of expeditionary travel. Space-based observations are probably the most cost-effective way to map remote reefs (Mumby et al. 1998) and, using change analysis, to observe temporal changes in coral communities. Simply stated, the question becomes whether remote sensing can be used to follow changes in coral reef biodiversity.

We explored the utility imagery from operational satellites for detecting and mapping gross change in coral reef communities to provide estimates of coral reef health and change over time. As a test case, we chose to evaluate the utility of Landsat thematic mapper (TM) imagery to detect gross changes in coral reef communities that resulted from the mass mortality of the spiny black sea urchin (*Diadema antillarum*) in 1983–1984 (Lessios et al. 1984). This basin-wide mass mortality dramatically lowered rates of herbivory on virtually all Caribbean reefs. Subsequently, algal populations flourished and overgrew large areas of substrate, including coral, sponges, sessile gorgonians, red crustose algae, and other members of the benthic reef community (Dustan 1987, 1999; Curran et al. 1994; Hughes 1994). Approximately 16 years after the initial mass mortality event, *D. antillarum* populations are showing only slight signs of potential recovery (Lessios 1995).

Scientists do not yet know definitively what is causing the decline of some of the reefs in the Caribbean. It is suspected by many researchers that multiple stressors, including direct and indirect anthropogenic effects such as land-based sources of pollution and overfishing, are at the root of the problem (Rogers 1985; Tomascik & Sander 1987; Dustan 1999; Hay 1999). Furthermore, in the Florida Keys we seem to be observing environmental effects cascading through multiple ecosystems. The Florida Reef Tract is at the downstream end of the hydrology of south Florida, a system that has experienced explosive human population and agricultural growth over the last 50 years. In addition, the Gulf Stream, which washes over the seaward margin of the reef tract, carries materials from elsewhere in the Caribbean and Gulf of Mexico, including the Mississippi River basin. Materials from watersheds as distant as the Amazon and Orinoco Rivers of South America and from atmospheric transport of African agricultural dust could contribute additional stress to the reef system (Shinn et al. 2000).

### Remote-Sensing Imagery

We used Landsat TM imagery to investigate community-scale reef change from 1982 through 1996. The TM sen-

sor has a spatial resolution of 30 m and three visible broad-spectrum bands (red, green, and blue) (Markham & Barker 1985). The Landsat TM and the System Pour l'Observation de la Terre (SPOT) provide the best operational remote-sensing platforms for locating reefs and mapping their general zonation patterns and dominant benthic communities (coral, seagrasses, sand) (Biña et al. 1978; Maniere & Jaubert 1985; Jupp 1986; Kuchler et al. 1988; Bour & Pichon 1997; Mumby et al. 1998; Dustan et al. 2000). The blue band of TM probably gives it a slight performance edge (Mumby et al. 1997). The first TM instrument was launched aboard Landsat 3 in July of 1982 and began capturing images shortly after launch. Control of the spacecraft and image archival was transferred from the National Aeronautics and Space Administration to the EROS Data Center in 1984. The data stream has been maintained through a series of Landsat sensors, most recently Landsat 7, which was launched on 15 April 1999.

### Reefs of the Florida Marine Sanctuary

Coral reefs throughout the Florida Keys have undergone catastrophic ecological degradation over the last 25 years. Carysfort is the only reef for which this long-term change has been documented with quantitative line-transect studies. Carysfort is the richest and most diverse reef in the northern Florida Keys (Dustan 1985a) and lies at the northern seaward edge of the Florida Keys National Marine Sanctuary (Fig. 1). The reef community was first quantitatively surveyed in 1974 from the reef flat to the deepest depth of coral (20 m) on the inner reef terrace (Dustan 1985b). The second survey occurred in 1982–1983 (Dustan & Halas 1987), and the site has been included in other reef-monitoring projects, principally a series of multi-method surveys featuring photostation analysis (Porter & Meier 1992). Since 1996, Carysfort Reef has been sampled annually by the U.S. Environmental Protection Agency Coral Reef Monitoring Project (Dustan 2000; Porter et al. 2001).

In 1975 the shallow seaward reef zones of Carysfort Reef were dominated by populations of elkhorn coral (*Acropora palmata*), which formed large monotypic stands typical of Caribbean coral reefs (Goreau 1959). *A. palmata* was the “signature coral” of the shallow-water reefs of the Florida Keys. The highest living coral cover on Carysfort Reef occurred on the seaward side of the shallow reef flat in the *A. palmata* zone.

Since 1975, most of the *A. palmata* colonies have died, and the species has recently been considered a possible candidate for inclusion on the Endangered Species List. Living coral coverage, estimated at 40% of the total cover in 1975, increased to a surveyed 60% in 1982–1983 and then began to fall. The increase between 1975 and 1983 was due principally to physical breakage. Large, three-dimensional colonies were broken and lay strewn about

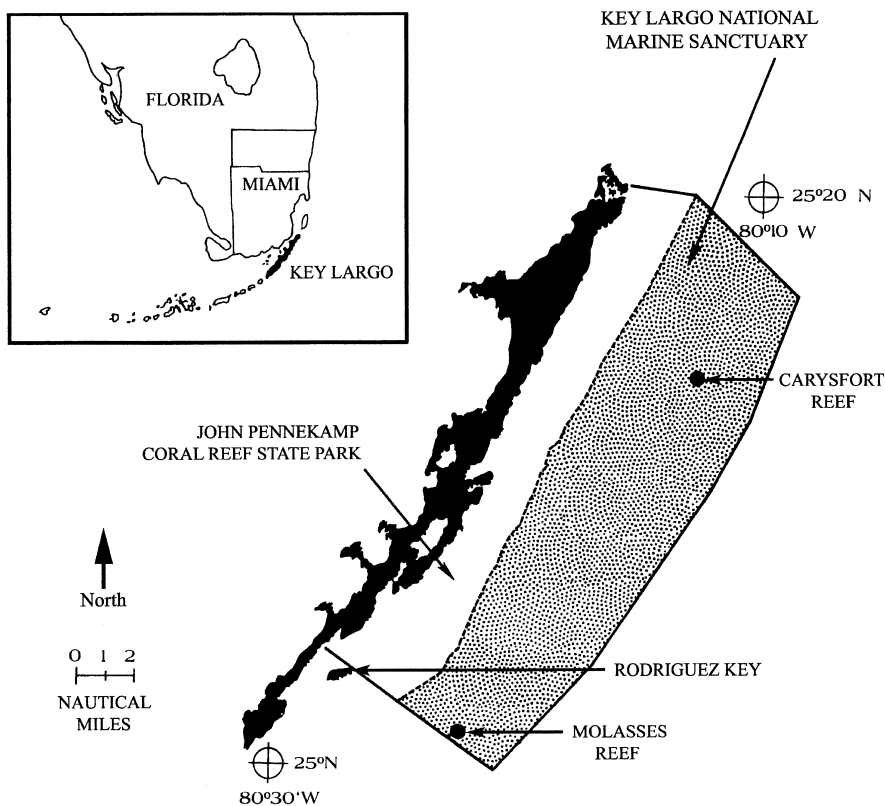


Figure 1. Location map of south Florida and the Florida Keys showing study sites for coral reefs, Rodriguez Key, and the Key Largo habitats.

the reef substrate, which effectively increased coral coverage while decreasing mean colony size (Dustan & Halas 1987). The mass mortality of *D. antillarum* occurred in Florida during August of 1984, which further exacerbated conditions on Carysfort Reef through a dramatic reduction in grazing pressure (Hughes 1994). Algal turf communities began to form in large areas of the shallow reef that were encrusted with highly reflective crustose coralline algae. By 1985, many of the coral fragments had died and many regions of the former *A. palmata* zone were covered with algal turf communities. High rates of mortality were documented between 1984 and 1991 (Porter & Meier 1992). Then, in 1996, mortality rates increased again with the outbreak of a seemingly new virulent form of white plague disease termed white pox. This disease specifically attacks *A. palmata*, killing large colonies within months (J. Porter, personal communication). The present coverage by *A. palmata* on Carysfort Reef is estimated at less than 5% percent (Dustan 2000). Living coral cover has also decreased dramatically in the deeper areas of the reef, although these are not visible in satellite imagery.

### Coral Reef Bio-optics

The formidable task for remote sensing is to relate the optical signal received in space above the atmosphere to the reef substrate, living or dead. Coral reefs develop to

their greatest extent in clear oligotrophic tropical seas where light intensities are high and nutrients tend to be the limiting factor. Because a large portion of the habitat is composed of living organisms, much of the upwelling reef signal is a function of the bio-optical state of the community. The high species diversity of coral reefs is reflected in the wide array of optical signatures emanating from the living reef substrate. Most of the important optical properties of the reef are related to photosynthetic pigments fixed in the benthic organisms, but there other pigments add both active and passive "color" to the reef (Mazel 1995; Meyers et al. 1999). Alterations of physical and ecological parameters (wave action, water temperature, nutrient loading, herbivory) can result in additional shifts in the community composition and thus the optical properties of the reef.

The upwelling optical signal is a blend of many complex spectral signatures caused by the spectral and spatial complexity of the habitat, reef geomorphology, and the optical properties of the overlying water column. As one moves away from the small scale of individual organisms, the signal becomes the product of a mixture of individual active and passive optical spectra. The base reef rock, calcium carbonate, is a bright white reflective substrate that rapidly becomes less reflective as it becomes covered with living organisms. The upwelling spectral signatures of reef zones are, for the most part, attributable to combinations of photosynthetic pigments contained in the dominant community members. Stony

and soft corals tend to be yellow-brown due to the light-harvesting peridinin-chlorophyll-protein complex of their zooxanthellae, green algae and seagrass derive their color from chlorophyll, and red calcareous algae are highly reflective in a broad band between 500 and 600 nm (Meyers et al. 1999; Dustan et al. 2000).

## Methods

### Satellite Image Time Series

An image time series of the Florida Keys was assembled from the archives at the Jet Propulsion Laboratory (JPL) and the U.S. Geological Survey (USGS) Center of Coastal Studies, St. Petersburg, Florida, via the Florida Marine Research Institute and purchased from the EROS Data Center. A time series of 22 images was subsequently assembled for the northern Florida Keys from 1982 to 1996. The earliest image, 1982, was captured shortly after launch but before TM became operational. We obtained copies of it from the EROS Data Center Scrounge File and from JPL. Unfortunately, neither copy possessed ephemeris data in its header file, so we could not correct the data to reflectance values. This precluded us from using its information when reflectance data were required, but we could use it when uncalibrated data were appropriate, as in band ratios and spatial-texture analysis. The other images, 1984–1996, were georeferenced and atmospherically corrected by the USGS (Raabe & Stumpf 1997). We used Erdas Imagine (version 8.3) for all subsequent image processing.

### Selection of Study Sites

We located reefs from a classified SPOT satellite image of the former Key Largo National Marine Sanctuary, now Florida Keys National Marine Sanctuary, which had been georeferenced to standard navigational charts of the National Oceanic and Atmospheric Administration. A hybrid, supervised-unsupervised classification using both panchromatic and multispectral images was used to delineate shallow benthic habitats, including reefs within the sanctuary boundaries (Dustan et al. 2000). Although the reef classes contained no information with respect to their within-habitat condition (i.e., coral vs. algal cover), their positions had been verified by sanctuary personnel as shallow reef areas under <1–2 m of water. Focusing on these areas provided the “cleanest” reef signals because the shallow depths would have minimal signal distortion due to water-column attenuation (including tidal depth), which can alter the spectral shape and magnitude of the upwelling benthic signal.

Using the classified SPOT image as a template, we subset areas of interest (AOI) from the TM image time series

to provide a set of cloud-free experimental and reference samples for investigating the magnitude and phenology of change. Each AOI of a time series was then accurately coregistered and precisely matched to provide a “best fit” image-to-image registration. Molasses and Carysfort Reefs were the principal focus of the study. Rodriguez Key, a small mangrove island, is a natural, undeveloped vegetated terrestrial habitat. A portion of the Key Largo mainland is an urbanized area that has changed dramatically from 1982 to the present, with the exception of a mangrove forest located near the southern end of the AOI. We also selected two sandy areas in shallow water, White Banks, to represent a high-reflective-end member that should not change much over time. An offshore AOI was selected in the axis of the Florida Current to represent the bottomless ocean as a low-reflective-end member that should also be relatively invariant in TM imagery.

### Image Analysis

The pixels from each selected habitat AOI were subset, and the mean pixel brightness values (BV) for each band (blue, green, and red) were compared between cloud-free images. Such data form the basis of mapping habitats with cluster and principal components analysis (Jensen 1996; Holden & Ledrew 1998). We also examined changes in spectral-band ratios because they are normalized measures that are less sensitive to atmospheric conditions, preprocessing, and calibration drift in satellite sensors. Also, band-ratio calculations form the basis of terrestrial vegetation indices (NVDI) and marine bio-optics (Smith & Baker 1978; Baker & Smith 1982).

Because reefs exhibit distinct patterns of zonation, we thought that a measure of spatial patchiness might reflect the distribution of reef zones and some indication of their variability over time. In two dimensions, texture is a measure of spatial heterogeneity used to identify objects or regions of interest within remotely sensed aerial photographs, airborne digital images, or satellite images (Haralick et al. 1973; Jensen 1996). In this context, texture is an index of similarity within a connected set of pixels, or neighborhood. Texture has traditionally been calculated as a function of the frequency of a particular pixel brightness (BV) from an odd-numbered pixel window ( $3 \times 3$ ,  $5 \times 5$ , etc.), or kernel, in two-dimensional imagery (Hsu & Burright 1980; Jensen 1996). In ecological terms, texture may be a proxy measure of habitat heterogeneity to the extent that pixel brightness reflects habitat differences.

Texture analysis can also be applied to the temporal domain to examine change over time at the scale of individual pixels, each representing the same geographic point on the earth. The spatial (x, y) dimension is held constant across the time series, and a sample statistic (i.e., standard error of the mean) is calculated for each

pixel location of each specific band (Dobson 1998). Great care must be used to precisely coregister the images so as not to introduce error from misregistration. These data can be visualized as a three-dimensional image in which the x, y dimensions represent geographic points and variability over time as the z dimension. High temporal texture is a measure of heterogeneity (change in pixel brightness over time), whereas areas with low temporal texture signify little or no change. The output is an image of the individual pixel-to-pixel variability over time.

We calculated temporal texture indices as the standard deviation of pixels brightness over time at each x, y location in the blue, green, and red bands of all the cloud-free images in each AOI image set (Dobson 1998). We also computed the coefficient of variation (COV) from the standard deviation to allow us to compare the variability of pixels independent of the magnitude of pixel brightness (Sokal & Rohlf 1995):  $COV = STD / \text{mean} * 100$ , where STD is the temporal texture (standard deviation of pixel brightness [BV] at each pixel x, y, for the cloud-free image observation data set) and mean is the mean at pixel x, y for the cloud-free image observation data set.

## Results

### Spectral Reflectance and Bank Ratios

A cluster analysis of all sites using the mean pixel brightness of the red, green, and blue bands of each AOI site divided the AOIs into three quasi-distinct clusters: terrestrial habitat, sand, reef, and offshore habitat (raw data available from authors upon request). The offshore waters of the Gulf Stream displayed the least variation and the terrestrial urbanized environment the greatest. An examination of reflectance over time revealed no statistically significant trends between 1985 and 1996 for either Molasses or Carysfort reefs (Fig. 2). Both reefs exhibited high blue reflectance in 1982, which then dropped over time to a minimum in 1988. One must bear in mind that the 1982 data may be flawed. On Carysfort values then rose slightly through 1993 and then dropped in 1996. Red BV values parallel blue values. Discounting 1982, green BV values rose from 1985 through 1988 and then dipped and rose slightly through 1993. Molasses Reef was more variable than Carysfort. Although no clear patterns are evident on either reef, the reefs did appear to change color slightly over time. Spectral shifts were not as evident in terrestrial imagery of Rodriguez Key, a mangrove island (Fig. 3).

TM spectral-band ratios for Carysfort Reef increased from 1985 to 1988 and then decreased through 1993 (Fig. 4). The shifts at Carysfort Reef seem to parallel the temporal trends in pixel brightness, suggesting that

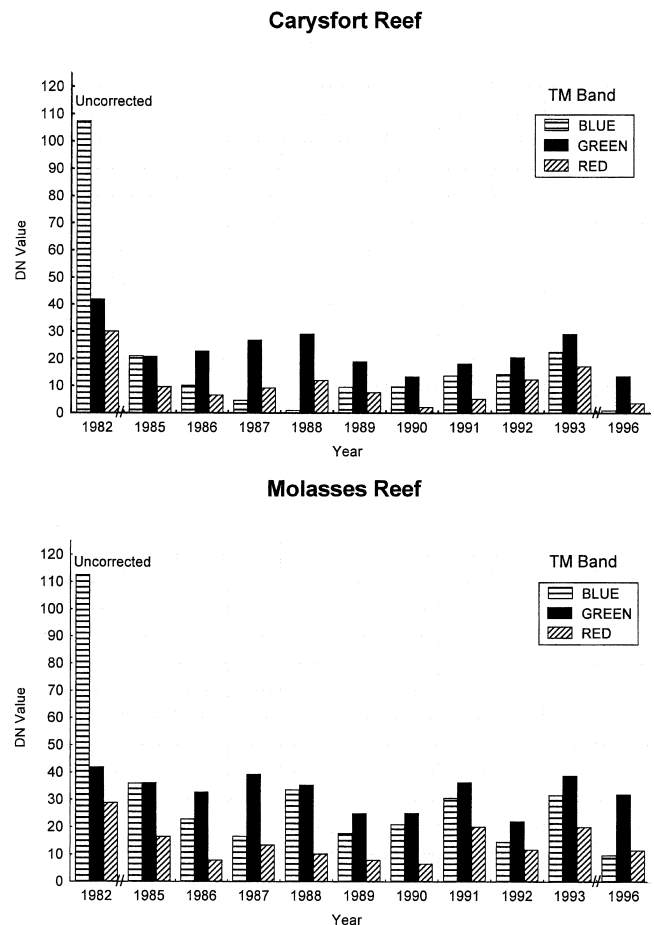


Figure 2. Time series of Landsat thematic mapper mean spectral reflectance (DN [digital numbers] value).

changes occurred in both reef color and albedo (substrate reflectivity). The reef became almost 50% brighter in the green region of the spectrum. Molasses Reef exhibited more variability in the green/red ratio and less in the blue/green ratio. But neither of these data sets demonstrate any statistically significant trends over the entire time series.

### Texture Analysis

An examination of spatial variability for Rodriguez Key yielded values ranging from 1 to 3 SD with no apparent significant trends over time (Fig. 3). Molasses and Carysfort reefs exhibited higher spatial texture than Rodriguez Key, values ranging from 1.5 to almost 8 (Fig. 5). Texture on Carysfort Reef did not display clear trends, whereas Molasses Reef displayed more pronounced variability, with apparent peaks in 1985, 1991, and 1996.

Temporal texture calculated for imagery of Rodriguez Key revealed that the terrestrial vegetation was less variable than the shallow-water zones surrounding the island (Fig. 6). Temporal textural analysis of a portion of the Key Largo mainland revealed a pronounced change

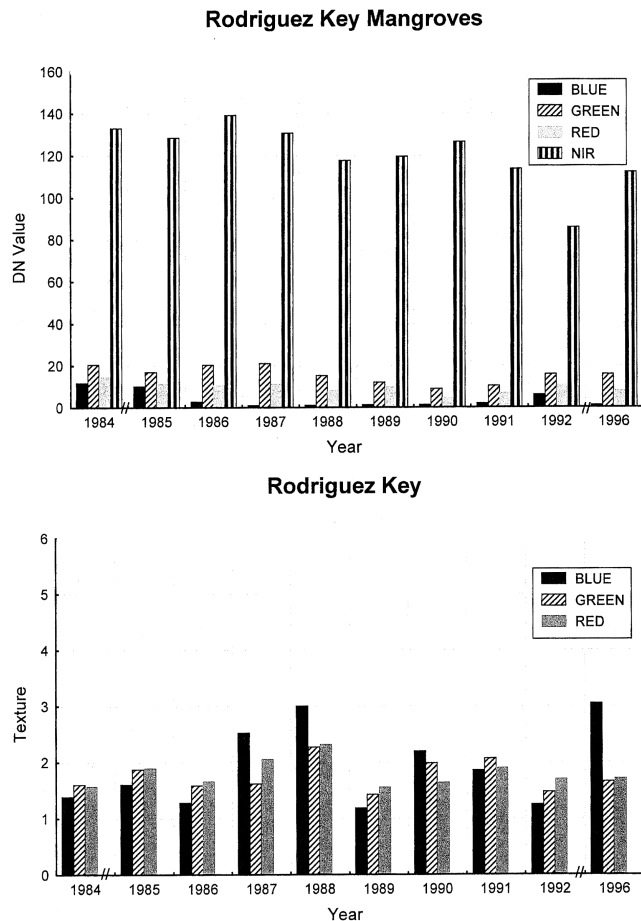


Figure 3. Time series of Landsat thematic mapper mean spectral reflectance (DN [digital numbers] value) (top) and spatial texture (index of similarity within a connected set of pixels) (1984–1996, bottom) of Rodriguez Key.

between 1984 and 1996, except in the area of an undeveloped mangrove forest (Fig. 6). Areas of high reflectivity represent the urban landscape and display complex patterns of temporal texture.

Temporal texture on Molasses and Carysfort reefs shows that the seaward shallow portions of these reefs have undergone the greatest amount of observable change. Back reef areas and surrounding seagrass beds are considerably less variable over time. The highest values occur on the seaward edge of the shallow reefs, the *Acropora palmata* zone (Figs. 6d & 6e, Fig. 7).

Because we do not know how to gauge the significance of temporal texture, we generated an image in which the standard deviation around the mean COV was binned into five categories  $\pm 2$  SD around the mean COV in an attempt to place confidence intervals around the mean coefficient of variation. In normally distributed data, 95% of the items fall between  $\pm 1.96$  SD of the mean (two-tailed), so any pixels  $\geq 2$  SD above the mean may be considered significantly different from the popu-

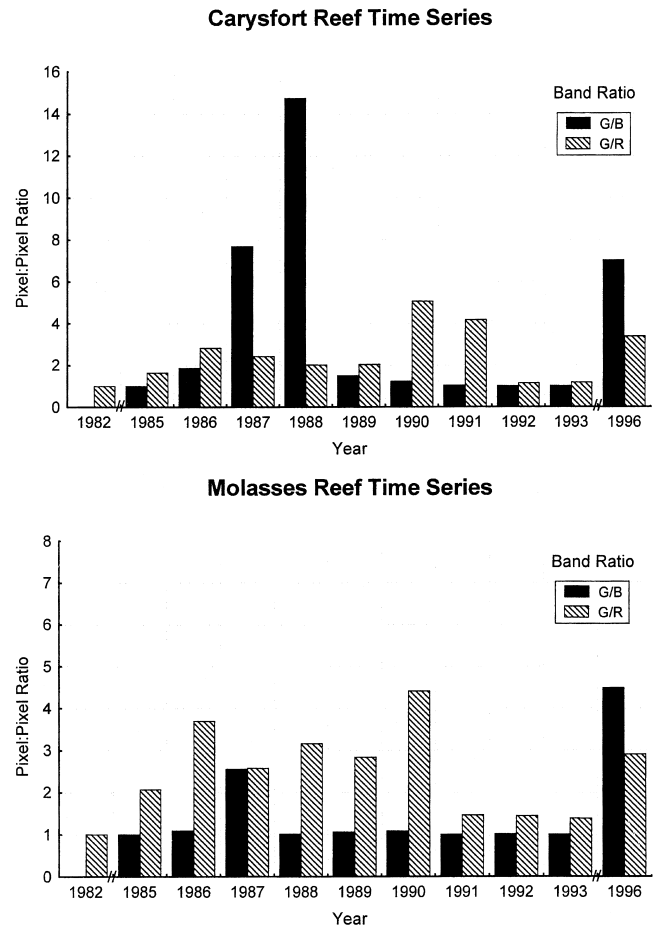


Figure 4. Time series of Landsat thematic mapper spectral-band ratios for Molasses and Carysfort reefs.

lation. The visualization of this revealed a region of significant pixels precisely in the area where the *Acropora palmata* zone has been decimated (Fig. 8).

## Discussion

Time-series analysis can detect and statistically parameterize patterns and trends in observations through time, such as the fundamental phenology characteristics of a landscape (Olsson & Eklundh 1994). The launch of Landsat TM in 1982 began the record of multispectral scanner data with red, green, and blue visible bands at a spatial scale (30 m) compatible with reef scales. The Landsat program is the oldest source of global calibrated high-spatial-resolution measurements of the Earth's surface that can be compared to previous data records. Unfortunately, until the launch of Landsat 7 in 1999, there never was a systematic effort to collect data over coral because many are in remote areas and the data must be recorded and later downloaded to a receiving station. Coverage was more complete over the Florida Keys, which are part of the continental United States.

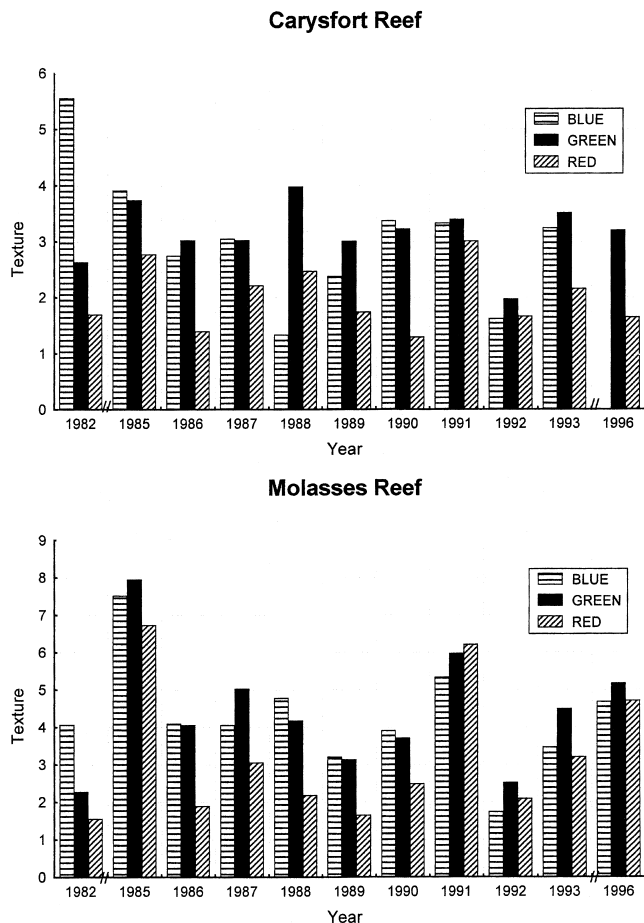


Figure 5. Time series of spatial texture (index of similarity) within a connected set of pixels for Carysfort and Molasses reefs, 1982–1996.

Interpreting coral community change through an examination of spectral reflectance required some information on the optical properties of the reef community. In situ optical spectra suggest that reef corals can be distinguished from green and red algae on the basis of spectral reflectance and albedo (Holden & Ledrew 1998; Meyers et al. 1999). Likewise, reef habitats possess different spectral reflectances that can be used to generate habitat classifications and distinguish reefs from their surrounding substrates. But this may not always be possible with broad-band, multispectral imagery because information is lost when the fine-scale radiometer measurements are summed into the broad TM bands. Recent modeling studies on radiative transfer of these signals suggest that the blue and green wavelengths propagate through the water column and atmosphere more efficiently than longer red wavelengths (Lubin et al. 2001). The temporal patterns of reef reflectance we gleaned from TM satellite data hint that the substrate became greener over time and, at the same time, reef albedo decreased. Such shifts in optical signatures are consistent with the hypothesis of increasing algal populations,

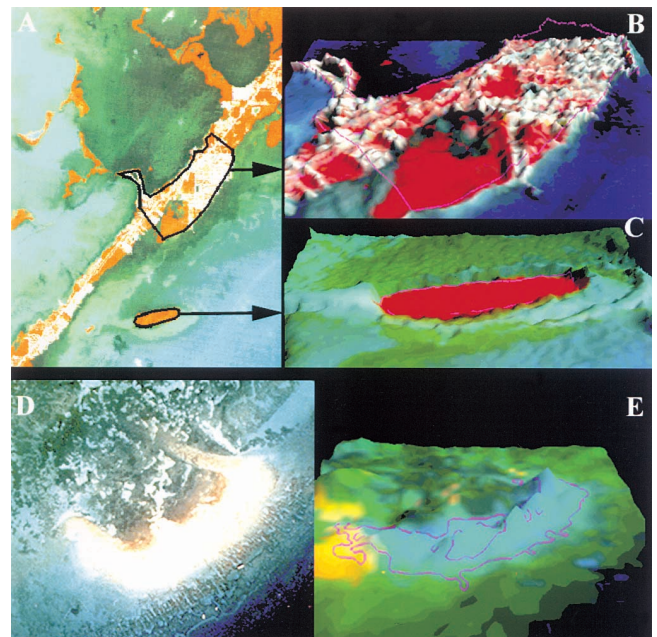


Figure 6. Three-dimensional visualization of habitat variability as depicted by temporal texture. (a) A two-dimensional Landsat thematic mapper image for Key Largo. Temporal texture for (b) Key Largo and (c) Rodriguez Key. Temporal texture is the vertical axis in these three-dimensional models of change. Rodriguez Key shows little change, whereas the Key Largo mainland has undergone considerable alteration. Note the relatively “flat” region in southeast Key Largo. Although much of the island has been developed, the mangroves are protected. (d) Molasses Reef shown in an aerial photograph. (e) Temporal texture in which a modified true-color version of the image subset area of interest is draped over the “wire frame” to show the general habitat features. The shallow reef, bright yellow, shows the seaward edge of the reef. The spur-and-groove zone lies seaward (right) of the shallow reef.

which would be greener and darker than corals. This point is verified by in situ observations showing that the reef community has changed from a coral-dominated substrate to one with increasing fleshy algal coverage (Dustan 1999).

Although it is speculative to attach a biological meaning to texture analysis of AOIs, the heterogeneity could be generated by habitat patchiness or annual phenology (seasonal change). On the reefs, clear trends in decreasing patchiness would be consistent with the observed loss of corals and subsequent overgrowth of the substrate by algae. Shallow-water corals tend to be distributed in zones and patches within areas that may actually be supercolonies produced through breakage and subsequent recovery. If these patches were to die and then, in turn, be replaced with algae, the spatial heterogeneity of



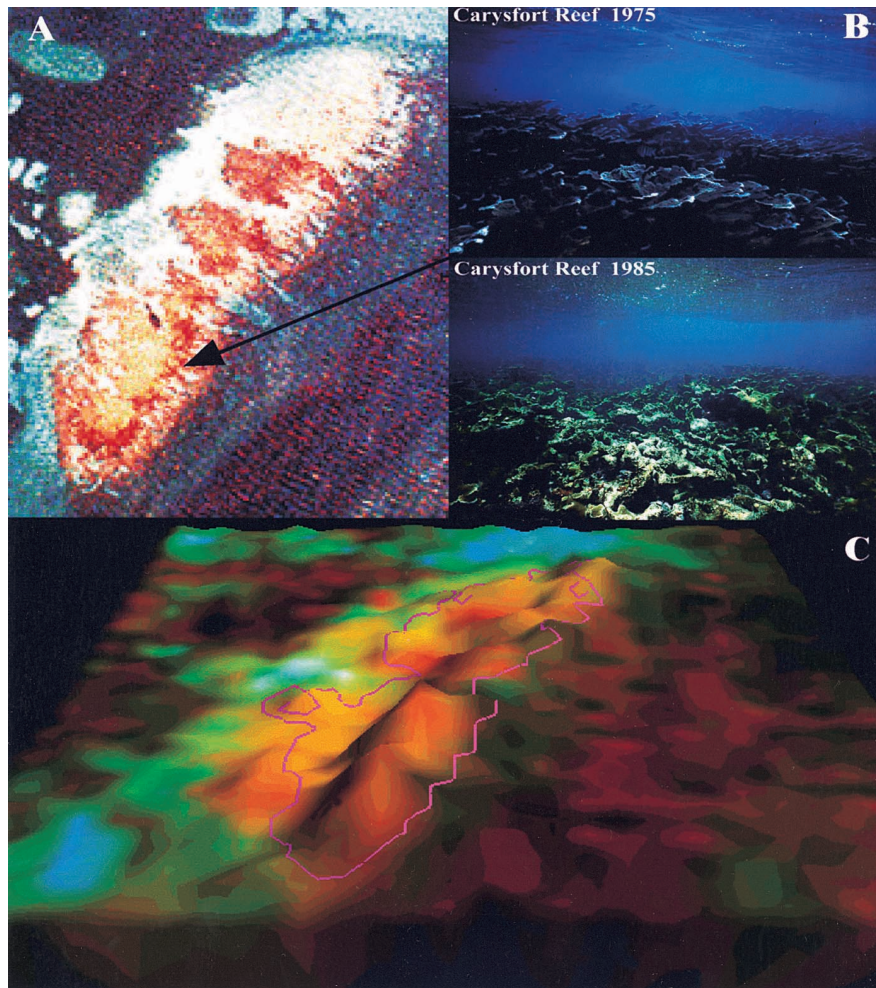


Figure 7. A three-dimensional visualization of habitat variability on Carysfort Reef as depicted by temporal texture. (a) A digital scan of a NAPP high-altitude aerial photograph showing the general reef features. Shallow areas are bright yellow, and brown areas are the reef flat and the seaward edge of the shallow reef. The lighthouse and its shadow can be seen above and to the left of the arrow tip. The arrow points to the *A. palmata* zone, which can be seen (b) underwater in a pair of photographs taken from the same vantage point 10 years apart. (c) A three-dimensional visualization of reef change with standard deviation of pixel brightness as the vertical axis.

the reef substrate would increase at first as the corals died and then decrease over time as the algae overgrew the dead skeletons.

Computations of temporal texture revealed patterns of habitat variability and rendered three-dimensional representations of change for the terrestrial and submerged sites. Although we focused on reefs, the other sites provided information that helped us interpret temporal texture. The highly reflective sand of White Banks and the offshore ocean, which represented areas at the high and low ends of the spectrum, showed little or no change in temporal texture analysis in any spectral bands. These areas are different from each other, but they are both relatively stable and should not show significant change over the length of the time-series analysis.

The visible blue band (TM band 1) discriminated the changes in the urbanized system for terrestrial sites (Key Largo and Rodriguez Key) most efficiently. We had expected that the infrared band (TM band 4) would be most efficient at discriminating change but realized that the mode of change for the urbanized area is from vegetation to impervious surface and bare carbonate sands. The blue visible band showed the greatest difference be-

tween vegetation (blue is absorbed) and highly reflective impervious surface (concrete) and carbonate sand.

Temporal texture revealed that the terrestrial vegetation of Rodriguez Key has been relatively invariant, whereas the shallow-water zones surrounding the island have been more dynamic. The island is a protected and undeveloped mangrove ecosystem that is located just outside the boundary of John Pennekamp Coral Reef State Park. The island is close to the mainland of Key Largo, however, and its shallow-water habitat is exposed to increased nutrients and land-based pollutants characteristic of urbanization, and to the normal perturbations of a nearshore environment.

The mainland of Key Largo showed pronounced change between 1984 and 1996, except in the area of an undeveloped mangrove forest. During the period, Key Largo underwent extensive residential and commercial development. The high variability results from land clearing, followed by construction and subsequent landscaping. This occurred on a parcel-by-parcel basis, with the average residential lot being just slightly larger than the size of a TM pixel,  $30 \times 30$  m. Change along the path of U.S. Route 1, a major highway, is revealed as a linear feature



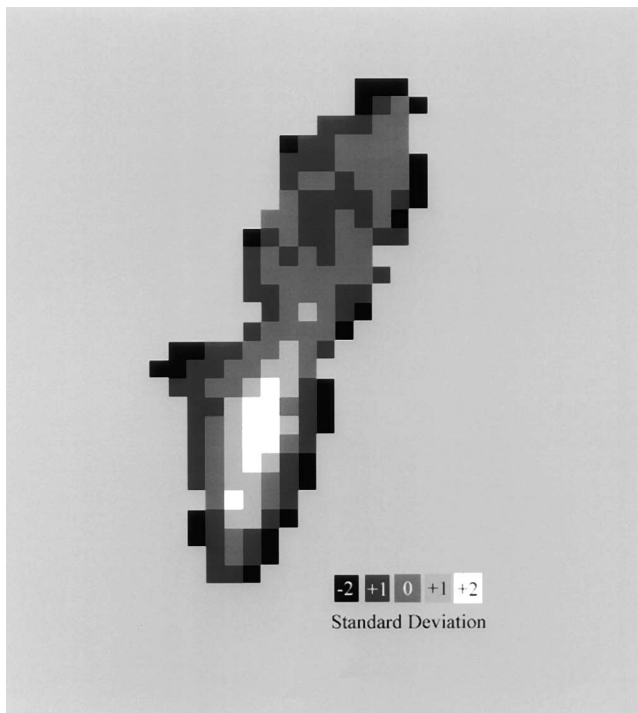


Figure 8. Spatial distribution of the standard deviation of the mean coefficient of variation for the temporal texture of Carysfort Reef.

that runs the length of the Key Largo AOI. The roadside underwent extensive commercial development during the time period of the study. In all these analyses, the highly variable sites were places that had been affected by human processes, whereas the natural ecosystems were less variable.

The greatest change in the reef habitats (i.e., in areas known to have changed from in situ field observations) was revealed by the red visible band (TM band 3). Water penetration is most efficient between the visible blue and green wavelengths around 485 nm, but the red portion of the spectrum showed the greatest variation. Because the dominant mode of change over the reef was from coral (which is yellow brown) to algae (which is blue green), the shift from the red to blue wavelengths appears to be an environmental signal identifying shifts in coral reef community from coral to algae. White sand environments (at the same depth) and deep water, which represent the high and low ends of the spectrum, showed little change in the visible red. This reinforced the notion that a shift in community structure (coral- to algal-dominated) influenced the bio-optical properties of the reef.

Temporal texture on Molasses and Carysfort reefs revealed that the shallow reefs have been more variable over time than their surrounding habitats. This may be due, in part, to the fact that water depths are deeper on the seaward sides, whereas the shallow waters behind

the reefs are principally seagrass beds, which may be less sensitive to change. Within the boundaries of the two reefs, the greatest amount of observable change occurred on the seaward edge of the reef crest, the *Acropora palmata* zone.

The changes we have observed in TM time series are in agreement with what is known about change in the Florida Keys. The process of urbanization has changed the mainland, and temporal texture has accurately depicted this process. Rodriguez Key has been relatively undisturbed, and estimates of temporal texture are low. Measures of reef spectral reflectance from space suggest that Molasses and Carysfort reefs have become greener and their albedo has decreased. Although both observations are consistent with increased algal growth, the trends are not significant. Finally, measures of temporal texture on these reefs suggest that change has been greatest where significant loss of coral has been recorded. On Carysfort Reef, temporal texture analysis revealed that the greatest rates of change occurred in habitats that have experienced near-catastrophic ecological change. The once dominant corals have died, and the substrates are overgrown by turf algae. Satellite data suggest that similar changes have occurred on Molasses Reef. Although underwater visual observations verify this analysis, there are no quantitative in situ time-series data to corroborate the findings.

To the best of our knowledge, this is the first time-series analysis of coral reef ecosystem variability based on satellite imagery. Our results demonstrate that thematic mapper images contain information that can be used to distinguish areas of long-term stability from areas of change in both terrestrial and benthic environments without the necessity of accurate target identification. It may be prudent, however, to invoke some caution in the interpretation of these patterns. Although spectral and albedo shifts were suggested, we have not been able to positively identify the type of change, only estimate its magnitude. The time series of satellite imagery we used is, in reality, a glimpse over time, and more images are needed to generate a more definitive, smoother time series. With additional information, the statistical power of the time-series analysis will greatly increase. It may even be possible to separate seasonal and long-term trends. Then we may be able to more fully relate the observed spectral patterns to changes in the coral reef community.

Our work suggests that temporal texture analysis can capture the spectral and textural variability of coral reef communities through time and space. The fact that temporal texture reveals change that is not readily apparent from optical properties suggests that the optical properties of ecological change may be more complex than previously considered. It also raises the possibility that measures of variability may be diagnostic without needing to generate a precise classification. This opens the

possibility that currently orbiting technology may be used to examine large areas of a reef tract for change. If changes are detected, more directed field studies and higher-precision remote sensing from aircraft or "next-generation" high-resolution orbiting sensors could be focused on these critical areas. Of equal or perhaps greater interest might be known reefs that do not show great change. Such natural experiments may be important in the design of nested-scale global coral reef monitoring.

## Acknowledgments

This work was accomplished with the help of many people. R. Stumpf and E. Raabe of the U.S. Geological Survey and P. Huohoulis of the Florida Marine Research Institute graciously provided imagery. L. Stuart, of the National Aeronautics and Space Administration (NASA)/GSFC, provided the "keys" to the Scrounge File at EDC, and T. Logan, of NASA/Jet Propulsion Laboratory helped locate early Landsat thematic mapper imagery. We thank M. Brill, V. Kosmynin, J. Leard, Q. Schuyler, and especially Erdas, Inc., for advice and technical expertise. Funding was provided by NASA (NAG8-1413) through the Center for Marine Conservation and the Jeanette and Lafayette Montgomery Foundation.

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